

Mouse Models of Syndromic Craniosynostosis

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Abstract

Craniosynostosis is a common craniofacial birth defect. This review focusses on the advances that have been achieved through studying the pathogenesis of craniosynostosis using mouse models. Classic methods of gene targeting which generate individual gene knockout models have successfully identified numerous genes required for normal development of the skull bones and sutures. However, the study of syndromic craniosynostosis has largely benefited from the production of knockin models that precisely mimic human mutations. These have allowed the detailed investigation of downstream events at the cellular and molecular level following otherwise unpredictable gain-of-function effects. This has greatly enhanced our understanding of the pathogenesis of this disease and has the potential to translate into improvement of the clinical management of this condition in the future.

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Craniosynostosis is a common feature of craniofacial birth defects, with a prevalence of 1:2,500 births [Cohen and Kreiborg, 1992]. It is characterised by premature fusion of calvarial bones and can occur along single or mul-

iple cranial sutures. Around 30% of craniosynostosis occurs within a characterised craniofacial syndrome (syndromic craniosynostosis) with a genetic cause, whilst the majority of non-syndromic cases have a de novo cause (non-syndromic craniosynostosis) [Johnson and Wilkie, 2011]. The molecular basis for craniosynostosis is complex: for example, a genetic cause such as a dominant mutation within one of the fibroblast growth factor receptor (*FGFR*) 1, 2, and 3 genes are well known; yet, environmental factors, most notably intra-uterine head constraint, have also been hypothesised as among the predisposing factors to this condition [Muenke et al., 1994, 1997; Reardon et al., 1994; Johnson and Wilkie, 2011]. The phenotypic consequence of craniosynostosis is skull shape distortion with secondary sensory-neurological deficits through an increase of intracranial pressure [Derderian and Seaward, 2012]. Typically, *FGFR* mutations are responsible for the crouzonoid phenotype comprising of complex craniosynostosis, midfacial hypoplasia, strabismus, and brachycephaly [Johnson and Wilkie, 2011]. As a result of craniosynostosis, symptoms include optic atrophy, blindness, and hearing deficits [Derderian and Seaward, 2012]. There is currently no pharmacological treatment for craniosynostosis, with repeating surgical modalities as the primary option to accommodate normal brain growth by correcting skull dysmorphology and reducing intracranial pressure, a procedure known as craniectomy [Johnson and Wilkie, 2011]. Specifically,

surgical interventions aim to re-open the suture (distractor osteogenesis) with calvarial remodelling [Park and Yoon, 2012].

Historically, a mutation in the *MSX2* (Msh homeobox 2) gene was first to be associated with syndromic craniosynostosis, eliciting a clinical phenotype known as Boston type craniosynostosis [Jabs et al., 1993]. Mutations in genes encoding FGFRs were identified later and are perhaps the most common genes involved in syndromic craniosynostosis [Wilkie, 2005]. The most notable characteristics of craniofacial dysmorphology are often referred to as the crouzonoid phenotype, with coronal synostosis being the most common type of suture fusion [Wilkie and Morriss-Kay, 2001]. This usually results from autosomal dominant mutations that constitutively activate the FGF receptor and as such can be thought of as gain-of-function (GOF) mutations [Wilkie, 2005]. A generalisation is that the craniofacial spectrum elicited by FGFRs signalling misregulation will depend on the tissue specificity and precise allelic mutation within the receptor gene [Wilkie, 2005]. Allelic mutations affecting the ligand-binding domain (S252, P253, C278, and C342) account for 80% of all craniosynostosis cases. An interesting observation first mentioned by Wilkie [2005] is that identical substitutions across all FGFR paralogues are conserved at equivalent positions along the gene. For example, an amino acid change within the linker region of each receptor such as Proline 250 to Arginine (p.Pro250Arg) gives rise to either Pfeiffer (FGFR1), Apert (FGFR2), or Muenke (FGFR3) syndromes, with coronal synostosis being a common phenotype of all 3 [Wilkie, 2005]. FGFR1, 2, and 3 are all expressed along the edges of the calvarial bones with FGFR2 predominant in the osteogenic front [Iseki et al., 1999; Johnson et al., 2000]. However, the spatial localisation of the various splice forms is not well characterised due to their high sequence homology. Instead, it is mainly through isoform-specific knockouts in mouse models that their individual functions have been delineated (see below).

Undeniably, mouse models have offered a significant platform to study human disease progression, and generating models carrying specific knockin mutations can help to address questions concerning the phenotypic diversity caused by the various mutations identified in patients. Whilst a large body of research has focussed on the genomic landscape, the biochemical and transcriptomic consequences that influence cellular activity *in vivo* still remains to be fully elucidated. In order to advance translation to clinical practice, it will be critical to address the aberrant mechanisms that lead toward these craniofacial

abnormalities. In this review, we will provide an overview of the currently available mouse models that have been associated with various forms of syndromic craniosynostosis (Table 1). Finally, we will draw conclusions about the work done so far and make suggestions where future research into this area is headed.

FGF Signalling-Related Mouse Models of Human Syndromic Craniosynostosis

Fibroblast Growth Factor Receptors

FGFR1

Mutations in *FGFR1* have been reported in Kallman, Jackson-Weiss, Muenke, and Pfeiffer syndromes [Ornitz and Itoh, 2015]. In addition to the common craniofacial abnormalities, severe Pfeiffer syndrome patients exhibit limb and digit abnormalities [Muenke et al., 1994]. Specifically, these patients have varying degrees of syndactyly, finger truncation, broad digits, and short limbs [Muenke et al., 1994]. The GOF p.P252R substitution responsible for Pfeiffer syndrome was originally identified in the early 1990s, affecting exon 5 of *FGFR1*, common to both splice forms [Muenke et al., 1994]. The mutation was eventually reproduced in the mouse genome, creating a model for Pfeiffer syndrome (*Fgfr1*^{P250R/+}) with bicoronal craniosynostosis along with enhanced expression of osteogenic genes [Zhou et al., 2000]. Additionally, these mice have increased cell proliferation at postnatal day 5 in the sutures. On the other hand, loss-of-function (LOF) mutations (i.e., G237S, P722H, and N724K) in this receptor are more usually associated with hormone dysregulation than with skeletal defects and are related to Kallman syndrome [Pitteloud et al., 2006]. *Fgfr1* is expressed prominently in the distal limb bud between mouse embryonic day (E) 8.5–12.5 and is required for its correct initiation and outgrowth [Li et al., 2005; Verheyden et al., 2005]. Conditional inactivation of *Fgfr1*^{-/-} in the limb bud mesenchyme (*T^{Cre}*) do result in long bone and digital defects during later stages of development, similar to those in Pfeiffer patients [Li et al., 2005; Verheyden et al., 2005]. Therefore, the differential phenotype elicited by LOF mutations in humans and knockout mice suggests dosage sensitivity of FGFR1 signalling.

Complete abrogation of FGFR1 signalling is highly potent, and embryonic lethality is consistently reported throughout the literature [Deng et al., 1994; Yamaguchi et al., 1994]. Multiple strategies have been adopted to ameliorate this problem, including generation of hypomorphic models by reducing the expression of full length

Table 1. Overview of mouse models that display features of a syndromic craniosynostosis phenotype

| Gene | Mutation/transgene allele | Human syndrome (OMIM) | Affected sutures | Mechanism | Reference |
|---------------|---|---|--------------------------------------|----------------|---|
| <i>Fgf9</i> | N143T | SYNS3 (612961) | coronal | LOF | Harada et al., 2009 |
| <i>Fgf3</i> | mutagenesis | Crouzon (123500) | coronal | overexpression | Carlton et al., 1998 |
| <i>Fgf4</i> | mutagenesis | Crouzon (123500) | coronal | overexpression | Carlton et al., 1998 |
| <i>Fgfr1</i> | P250R | Pfeiffer (101600) | coronal, interfrontal, sagittal | GOF | Zhou et al., 2000 |
| <i>Fgfr2</i> | C342Y | Crouzon (123500) | coronal | GOF | Eswarakumar et al., 2004 |
| | W290R | Crouzon (123500) | coronal | GOF | Eswarakumar et al., 2004 |
| | S252W | Apert (101200) | coronal, sagittal, lambdoid | GOF | Wang et al., 2005 |
| | S250W | Apert (101200) | coronal, sagittal, lambdoid | GOF | Chen et al., 2003 |
| | Y394C | Beare-Stevenson (123790) | coronal | GOF | Wang et al., 2012 |
| <i>Fgfr2c</i> | <i>Fgfr2c</i> ^{-/-} | NA | coronal | LOF | Eswarakumar et al., 2002 |
| | <i>Fgfr2c</i> flox, <i>Fgfr2c</i> flox ^{-/-} | NA | coronal | LOF | Hajihosseini et al., 2001 |
| <i>Fgfr2b</i> | <i>Fgfr2b</i> ^{-/-} | NA | squamous temporal-parietal | LOF | De Moerlooze et al., 2000 |
| <i>Fgfr3</i> | P244R | Muenke (602849) | coronal | GOF | Twigg et al., 2009 |
| <i>Twist1</i> | <i>Twist1</i> ^{+/-} | Saethre-Chotzen (101400) | coronal, sagittal, lambdoid | LOF | Chen, 1995; Behr, 2011 |
| <i>Tcf12</i> | <i>Tcf12</i> flox ^{-/-} , <i>Twist1</i> ^{+/-} , <i>EIIa</i> CRE/+ | Saethre-Chotzen (101400) | coronal, sagittal, lambdoid | LOF | Sharma et al., 2013 |
| <i>Id1</i> | <i>Id1</i> ^{+/-} , <i>Twist1</i> ^{+/-} | Saethre-Chotzen (101400) | coronal, sagittal, lambdoid | LOF | Connerney et al., 2008 |
| <i>Id3</i> | <i>Id1</i> ^{+/-} , <i>Twist1</i> ^{+/-} | Saethre-Chotzen (101400) | coronal, sagittal, lambdoid | LOF | Connerney et al., 2008 |
| <i>Mx2</i> | <i>Timp1</i> -P7H | Boston-type craniosynostosis (604757) | coronal, sagittal, lambdoid | GOF | Liu et al., 1995 |
| | CMV-P7H | Boston-type craniosynostosis (604757) | coronal, sagittal, lambdoid | GOF | Liu et al., 1995 |
| | CMV-WT | Boston-type craniosynostosis (604757) | coronal, sagittal, lambdoid | overexpression | Liu et al., 1995 |
| <i>Jag1</i> | <i>Jag1</i> ^{+/-} | Alagille (118450) | no phenotype | LOF | Yen et al., 2010 |
| | <i>Jag1</i> flox ^{-/-} , <i>Twist1</i> ^{+/-} , <i>Mesp1</i> CRE/+ | Alagille (118450) | coronal, sagittal, lambdoid | LOF | Yen et al., 2010 |
| <i>Gli3</i> | <i>Gli3</i> Xt-J/Xt-J | Carpenter (201000) | lambdoid | LOF | Hui and Joyner, 1993; Rice et al., 2010 |
| <i>Rab23</i> | <i>Rab23</i> ^{-/-} | Carpenter (201000) | embryonic lethal | LOF | Eggenschwiler et al., 2001 |
| <i>Megf8</i> | C193R | Carpenter (201000) | sutures not analysed | LOF | Aune et al., 2008 |
| <i>Masp1</i> | <i>Masp1</i> /3+/- (double KO) | 3MC (257920) | sutures not analysed | LOF | Takahashi et al., 2008 |
| <i>Masp3</i> | | 3MC (257920) | sutures not analysed | LOF | Takahashi et al., 2008 |
| <i>Hdac4</i> | <i>Hdac4</i> ^{-/-} | Brachydactyly mental retardation (600430) | sutures not analysed | LOF | Vega et al., 2004 |
| <i>Tgfbr1</i> | M318R | Loeys-Dietz (613795) | coronal | GOF | Gallo et al., 2014 |
| <i>Tgfbr2</i> | G357W | Loeys-Dietz (613795) | no suture phenotype | GOF | Gallo et al., 2014 |
| <i>Nell1</i> | WT (CMV) | NA | coronal, sagittal, posterior frontal | overexpression | Zhang et al., 2002 |
| <i>Axin2</i> | <i>Axin2</i> ^{-/-} | NA | coronal, interfrontal | LOF | Yu et al., 2005 |
| <i>Dusp6</i> | exon 3 STOP, <i>Dusp6</i> ^{+/-} | NA | coronal | LOF | Li et al., 2007 |
| | <i>Dusp6</i> ^{-/-} | NA | coronal | LOF | Li et al., 2007 |
| <i>Gdf6</i> | <i>Gdf</i> ^{-/-} | NA | coronal | LOF | Settle et al., 2003 |
| <i>Pdgfra</i> | D846V (R26R) | NA | coronal, interfrontal | overexpression | Moenning et al., 2009 |
| | D842V/+, <i>Meox2</i> CRE/+ | NA | coronal | GOF | He and Soriano, 2017 |
| | D842V/+, <i>Mesp1</i> CRE/+ | NA | coronal, lambdoid | GOF | He and Soriano, 2017 |
| <i>EphA4</i> | <i>EphA4</i> ^{-/-} | NA | coronal | LOF | Ting et al., 2009 |
| | <i>Twist1</i> ^{+/-} , <i>EphA4</i> ^{+/-} | NA | coronal | LOF | Ting et al., 2009 |
| <i>Runx2</i> | <i>Prx1</i> - <i>Runx2</i> | NA | pan-synostosis | overexpression | Maeno et al., 2011 |
| <i>Erf</i> | <i>Erf</i> ^{-/-} | NA | no phenotype | LOF | Papadaki et al., 2007 |
| | <i>Erf</i> flox, <i>Erf</i> flox/+ | NA | no phenotype | LOF | Twigg et al., 2013 |
| | <i>Erf</i> flox, <i>Erf</i> flox ^{-/-} | NA | coronal, sagittal, lambdoid | LOF | Twigg et al., 2013 |
| <i>Frem1</i> | Frameshift (T>C) at intron 25, <i>Frem1</i> bat/+ | NA | posterior frontal | hypomorph | Smyth et al., 2004 |
| | exon 2 deletion, <i>Frem1</i> QBrick/+ | NA | posterior frontal | LOF | Vissers et al., 2011 |

LOF, loss of function; GOF, gain of function; NA, not associated (with a human syndrome).

FGFR1, mutating binding sites for FRS2 on *Fgfr1*, or preventing TRK autophosphorylation [Partanen et al., 1998]. Additionally, Partanen et al. [1998] have achieved isoform-specific knockout to exons 8 (IIIb) and 9 (IIIc) by

inserting a stop codon into these exons. *Fgfr1b* appears to be the major player in axial skeleton development, as *Fgfr1b*^{-/-} mice display vertebrate column truncations and limb abnormalities, despite the craniofacial skeleton re-

mains largely normal. Thus, the lack of a craniofacial phenotype exhibited by FGFR1 LOF implies its role in craniofacial development is minor. However, the *Fgfr1c* knockout mouse is embryonic lethal, suggesting the importance of the mesodermal isoform in early embryogenesis [Partanen et al., 1998].

FGFR2

FGFR2 is a positive regulator for osteoblast differentiation and manipulating this signalling pathway has consequences for osteoblastogenesis. It is well characterised that *Runx2*, the master regulator for osteoblast differentiation, is downstream of FGFR2 signalling [Miraoui et al., 2009]. Therefore, a substantial proportion of clinical syndromes and bone diseases have been related to signalling misregulation caused by this receptor. The role of FGFR2 was first characterised using knockout models. Several groups have generated *Fgfr2* knockout lines with similar phenotypes, yielding a series of gastrulation, placental and osteogenesis defects [Arman et al., 1998, 1999; Xu et al., 1998; Yu et al., 2003]. The first FGFR2 knockout was generated by targeted disruption to the kinase domain of the receptor, preventing autophosphorylation [Arman et al., 1998]. Other *Fgfr2* knockouts followed, by disrupting immunoglobulin loops along the receptor gene [Xu et al., 1998]. Xu et al. [1998] generated a knockout by removing exons encoding the IgIII loop responsible for ligand specificity. Despite homozygous lethality at E10.5, this study was the first to gain insights into the role of FGFR2 in limb development as these mutants fail to develop limb buds due to a loss of paracrine signalling that is responsible for tissue outgrowth [Xu et al., 1998]. It was later discovered from the *Fgfr2b*^{-/-} model that the IIIb isoform is critical for limb outgrowth as these mice have a complete loss of the appendicular skeleton [De Moerloose et al., 2000; Revest et al., 2001]. FGF10 is a likely binding partner for FGFR2b as *Fgf10*^{-/-} mice exhibit striking similarities to *Fgfr2*^{-/-} mice [Min et al., 1998; Sekine et al., 1999]. On the other hand, *Fgfr2c*^{-/-} mice illustrate that this isoform is required for normal craniofacial development as bi-coronal synostosis and underdevelopment of the auditory bulla were reported characteristics [Eswarakumar et al., 2002]. Others have also generated conditional *Fgfr2* knockouts to study tissue-specific effects: conditional knockout in the mesenchyme using *Dermo1*^{Cre} leads to defects in both axial and craniofacial skeleton [Yu et al., 2003]. Specifically, these mice have decreased bone density, truncated femurs owing to insufficient chondrocyte and osteoblast proliferation, brachycephaly, and dwarfism [Yu et al., 2003].

A large cohort of characterised craniofacial syndromes is commonly associated with *FGFR2* germline mutations [Wilkie, 2005]. GOF mutations in the *FGFR2* gene are characteristic of Apert, Crouzon, and Beare-Stevenson syndromes [Wilkie, 2005] and establish that FGFR2 signalling is a key player in craniofacial development. Crouzon syndrome is most commonly caused by a substitution mutation in *FGFR2c* (FGFR2c-p.C342Y; at the DIII Ig loop) and is autosomal dominant [Reardon et al., 1994]. The substitution of a cysteine to a tyrosine residue results in the stabilisation of intermolecular disulphide bonds at the receptor extracellular domains, leading to constitutive activation [Eswarakumar et al., 2005]. The phenotypes associated with the IIIc isoform in Crouzon syndrome are mainly craniofacial, whilst the p.S252W mutation found in Apert syndrome is associated with additional limb phenotypes such as truncation and syndactyly, since the mutation affects both FGFR2 splice variants [Johnson and Wilkie, 2011]. Mouse models are available for the most common FGFR2 craniofacial syndromes: *Fgfr2c*^{C342Y/+} (Crouzon), *Fgfr2c*^{W290R/+} (Crouzon), and *Fgfr2*^{S250W/+} (Apert) [Chen et al., 2003; Eswarakumar et al., 2004; Wang et al., 2005; Mai et al., 2010]. A common characteristic in these models are shortened midface, brachycephaly, and coronal suture obliteration, which mimicks the human disease phenotype. Interestingly, none of these models, including Apert mice, display a limb phenotype. On a cellular level, these mutations affect FGFR2 function by altering osteoblast proliferation, differentiation, and apoptosis in the suture. Eswarakumar et al. [2004] reported around E13.5 an early increase in cellular activity at the osteogenic front that is responsible for suture obliteration in *Fgfr2c*^{C342Y/+}. Chen et al. [2003], however, reported increased apoptosis as being a key player for coronal synostosis development in a separate mouse model for Apert syndrome (*Fgfr2*^{S250W/+}).

It is not well understood how a separate allelic mutation, also affecting the transmembrane domain of FGFR2, gives rise to Beare-Stevenson syndrome (*Fgfr2*^{Y394C/+}) [Wang et al., 2012]. Similar to the C342Y mutation, FGFR2-Y394C stabilises intermolecular bonds of unpaired cysteine residues leading towards constitutive activation. However, despite showing craniofacial similarities, Beare-Stevenson patients have additional skin abnormalities including cutis gyrate (thickened scalp) and acanthosis nigricans (hyper pigmentation) [Wang et al., 2012]. A mouse model has been generated to study this mutation (*Fgfr2*^{Y394C/+}), but the pathogenic origin of the cutaneous phenotype still remains unclear [Wang et al., 2012]. In addition to introducing GOF mutations, increasing gene

dosage also allows the identification of novel phenotypes in animal models. For example, a detailed analysis of *Fgfr2c*^{C342Y/C342Y} homozygotes identified exencephaly, overt cleft of the secondary palate, and a series of segmentation defects along the axial skeleton [Peskett et al., 2017].

Due to a common craniofacial phenotype elicited in animal models for syndromic synostosis, a robust platform to test novel therapeutic approaches and evaluate the safety of potential clinical treatments is provided. For instance, Shukla et al. [2007] attempted to rescue the coronal suture in *Fgfr2*^{S252W/+} mice through knockdown of the RAS-MAPK pathway with short-hairpin RNA (shRNA) or MEK-ERK inhibition using U0126 treatment. Despite some rescue of the suture, longitudinal evaluation of these mice revealed growth restriction in a proportion of treated animals along with spontaneous unexplained death in others [Shukla et al., 2007]. Indeed, the activating nature of FGFR2 has led to the assumption that attenuation of downstream signalling is sufficient to rescue craniofacial malformations [Shukla et al., 2007; Pfaff et al., 2016]. Several studies were able to demonstrate this in vivo: Firstly, craniofacial morphology was rescued when a mutant *Frs2a* allele was introduced onto the *Fgfr2c*^{C342Y/+} mouse, which prevented activation of the downstream RAS-MAPK pathway [Eswarakumar et al., 2006]. Secondly, systematic MAPK knockdown using shRNA or U0126 treatment was also sufficient to rescue craniosynostosis in *Fgfr2*^{S252W/+} [Shukla et al., 2007]. However, the idea of simply dampening the signal as a potential therapy may well be over-simplistic given the complexity of pathogenic FGFR2 signalling. Snyder-Warwick et al. [2010] examined the nature of FGF signalling output in the palates of the Crouzon mouse model. The authors found that *Spry2*, *Spry4*, *Etv5*, and *Dusp6*, all direct targets of FGF signalling, were downregulated at multiple developmental stages [Snyder-Warwick et al., 2010]. At the cellular level, these embryos had reduced cellular proliferation that resulted in a delay to palatal shelf elevation. Moreover, isoform-specific knockout of *Fgfr2c* (*Fgfr2c*^{-/-}) was sufficient to phenocopy the effects of *Fgfr2c*^{C342Y/+} with apparent coronal synostosis [Eswarakumar et al., 2002]. The paradoxical nature of FGFR2c signalling remains to be elucidated, but it is generally accepted that an intricate balance of signalling activity is required for normal development.

FGFR3

FGFR3 is a negative regulator for bone formation [Deng et al., 1996]. A number of *Fgfr3* knockout lines using different targeting methodologies have been report-

ed, all showing consistent bone overgrowth phenotypes [Colvin et al., 1996; Deng et al., 1996; Eswarakumar and Schlessinger, 2007]. The most notable characteristic is that these mice are larger in size as a consequence of ectopic chondrogenesis [Colvin et al., 1996; Deng et al., 1996]. Despite this, their bones have increased porosity, most likely due to a reduction in bone mineralisation. Analysis of isoform-specific knockouts revealed that the *Fgfr3c* isoform is responsible for the hyperplastic phenotype [Eswarakumar and Schlessinger, 2007]. In turn, an activated FGFR3 pathway through GOF mutations in *FGFR3* leads to an increased negative regulation of endochondral bone formation and is associated with short-limbed dwarfism caused by skeletal dysplasias such as achondroplasia and thanatophoric dysplasia [Rousseau et al., 1994, Shiang et al., 1994, Bellus et al., 1995]. The first missense mutation for achondroplasia was identified as a glycine 380 to arginine substitution (FGFR3-p.G380R) within the transmembrane domain of FGFR3 [Shiang et al., 1994; Bellus et al., 1995]. This mutation decreases receptor trafficking from the membrane, resulting in increased levels of phosphorylation during exposures to FGF ligands and signalling activation [Monsonogo-Ornan et al., 2000]. Histological analysis reveals a saturation of FGFR3 at mutant mouse growth plates, coincided with fewer chondrocytes in growth plates and hypertrophic zones [Monsonogo-Ornan et al., 2000; Segev et al., 2000]. Several mouse models have been made for achondroplasia such as *Fgfr3*^{G374R/+} and *Fgfr3*^{G369C/+}, which also affect the transmembrane domain [Chen et al., 1999; Wang et al., 1999]. Other models integrated a transgene containing the human FGFR3-p.G380R cDNA into the mouse genome, phenocopying the human disease [Segev et al., 2000; Lee et al., 2017]. In addition to the dwarfism phenotype, these mice also display brachycephaly and brain distortion [Wang et al., 1999]. Thanatophoric dysplasia is the most severe form of dwarfism [Tavormina et al., 1995]. The genetic differences that separate achondroplasia and thanatophoric dysplasia can be explained by different modes of receptor activation. Mutations that result in achondroplasia are caused by ligand-dependent receptor over-activation, whilst mutant FGFR3 for thanatophoric dysplasia are constitutively active [Ornitz and Itoh, 2015]. Mutations responsible for thanatophoric dysplasia stabilises intramolecular bonds of FGFR3 at either the transmembrane domain (*Fgfr3*^{S365C/+}) or the ligand-specific domain (*Fgfr3*^{Y367C/+}) [Chen et al., 2001; Pannier et al., 2009; Ornitz and Itoh, 2015]. In humans, a further mutation affecting the TRK domain, e.g., FGFR3-p.K650E, was identified, but a mouse model is

not yet available, perhaps owing to the potency of mutations affecting the kinase domain [Ornitz and Itoh, 2015]. There have been reports linking craniosynostosis to achondroplasia and thanatophoric dysplasia in the literature, but these links are not yet well established. For example, some patients with thanatophoric dysplasia exhibit a cloverleaf skull, suggestive of severe craniosynostosis [Tavormina et al., 1995], another mutation for achondroplasia (FGFR3-p.A391E) has been identified in Beare-Stevenson patients [Meyers et al., 1995] and similarly in the mouse, where an isolated study reports coronal synostosis in *Fgfr3*^{G380R/+} [Lee et al., 2017].

The p.P250R mutation is the most common mutation identified in all 3 FGFR paralogues [Wilkie, 2005]. In FGFR3, this leads to Muenke syndrome, where unilateral or bilateral coronal synostosis is an apparent characteristic [Muenke et al., 1994]. The p.P250R mutation affects both FGFR3 isoforms and results in increased affinity for FGF ligands [Muenke et al., 1994; Wu et al., 2009]. A knockin of this mutation in the mouse recapitulated Muenke syndrome (*Fgfr3*^{P244R/+}) [Twigg et al., 2009]. However, the craniofacial phenotype was incompletely penetrant due to background differences between mouse strains. Despite the variability observed in the general craniofacial skeleton, it has been a useful mouse model for studying inner ear development [Mansour et al., 2009; Mansour and Urness, 2013]. Muenke individuals were reported to have poor sensory reception towards the low end of the auditory spectrum [Mansour et al., 2009]. Analysis of the *Fgfr3*^{P244R/+} mouse identified multiple disruptions to the cochlear duct cytoarchitecture with alterations to the overall balance of support cells, with bias towards Dieter cell fate differentiation [Mansour et al., 2009; Mansour and Urness, 2013]. This change of fate was largely due to the mutation causing the receptor-losing ligand specificity, allowing ligands to bind promiscuously to both FGFR3b and FGFR3c isoforms [Mansour and Urness, 2013]. Genetic rescue of the ear phenotype can be achieved by reducing expression of *Fgf10*, a ligand specific to both the FGFR3b isoform, in compound mutants (*Fgfr3*^{P244R/+}; *Fgf10*^{+/-}) [Mansour and Urness, 2013]. Perhaps this study offers a useful insight into the reason why craniosynostosis does not develop in the Muenke mouse model, since in addition to background strain effects, available ligands in the coronal suture can act as limiting factors to the proposed phenotype.

FGF Ligands

The embryonic coronal suture expresses a repertoire of FGF ligands [Hajihosseini and Heath, 2002]. However, it

is not known how FGF ligands coordinate craniofacial development or regulate suture patency. The question is complex largely due to FGF ligands having multiple affinities toward different FGF receptors [Zhang et al., 2006]. Therefore, abrogation of FGF genes in vivo is likely to result in a redundant phenotype [Wright and Mansour, 2003; Zhang et al., 2006; Barak et al., 2012]. In light of this, determining whether a phenotype is a consequence of a single FGF ligand or a combination working synergistically remains a challenge. FGF ligands are abundant during development, and any genetic perturbation will most likely result in defects to organogenesis. One of the main purposes of FGF signalling in development is to mediate cross talks between the mesenchyme and epithelium [Ornitz and Itoh, 2015]. The most common FGF ligands involved in this process include epithelially expressed FGF9 and FGF10 in the mesenchyme, each signalling reciprocally to their tissue-specific FGFR isoforms [Ornitz and Itoh, 2015]. An example of tissue-specific interaction can be seen in the developing limb bud, which institutes a positive feedback loop regulating its outgrowth [Revest et al., 2001; Li et al., 2007]. Thus, genetically disrupting the tight coordination results in a series of skeletal dysplasias in the axial skeleton, largely affecting bone mass, densities, and stunted growth [De Moerlooze et al., 2000; Revest et al., 2001; Eswarakumar et al., 2002, 2004]. In addition to genetic approaches, surgical bead implantations soaked in different FGF ligands have been fundamental to understanding osteogenesis in vivo [Iseki et al., 1999]. Explicitly, this classical embryology approach is well characterised to investigate the impact of specific ligands on the calvaria, e.g. FGF2, to investigate ectopic osteogenesis [Iseki et al., 1999]. All the FGF ligands are expressed in the coronal suture with the exception of FGF3 and FGF4 [Hajihosseini and Heath, 2002]. To date, there has not been a report of syndromic craniosynostosis associated with ligand function other than FGF9, although mutations in *FGF3*, *FGF8*, and *FGF10* are sufficient to disrupt overall craniofacial development [Ornitz and Itoh, 2015].

Multiple synostoses syndrome 3 (SYNS3) is characterised by multiple fusion of synovial joints in the axial skeleton [Wu et al., 2009]. It is autosomal dominant and is caused by a missense mutation in FGF9 (FGF9-p.S99N) [Wu et al., 2009]. A phenotype closely resembling multiple synostoses syndrome in the mouse, with fusions of the elbow and knee, has been reported in the *Fgf9*^{N143T/+} mouse [Harada et al., 2009]. In addition to elbow-knee synostoses, these mice exhibit coronal synostosis. The consequence of the mutation has led to an LOF for FGF9-heparin binding, which affects overall FGFR signalling

potency. This protein interaction impairment resulted in hyper-diffusibility of the ligand in the extracellular matrix, encroaching into the joint and suture mesenchyme to induce synostosis. Additionally, mouse mutants carrying the missense mutation have ectopic expression of multiple osteoblast precursor markers such as *Runx2* and *Osteopontin* in the coronal suture mesenchyme at E16.5 [Harada et al., 2009]. FGF9 has high affinity towards the IIIc isoforms, in particular to FGFR3c [Zhang et al., 2006]. Thus, coronal synostosis for Muenke syndrome is indirectly linked to FGF9, as the FGFR3-p.P250R mutation causing Muenke syndrome affects the affinity of FGFR3c to FGF9 [Muenke et al., 1997; Harada et al., 2009].

Due to the promiscuity of ligand-receptor interaction, it is possible that ectopic expression of FGF ligands can also drive tissue-specific phenotypes, provided the receptors are expressed in the right tissue. In this scenario, Carlton et al. [1998] successfully phenocopied the Crouzon mouse model (*Fgfr2c*^{C342Y/+}) by disrupting the intergenic regions of *Fgf3* and *Fgf4*, normally absent from the wild-type suture, with midfacial hypoplasia, brachycephaly, and bi-coronal synostosis [Carlton et al., 1998]. Phenotypic redundancy is a consequence of ligand compensation. For example, in respect to FGF9, a fully penetrant urogenital tract defect is only observed when both *Fgf9* and *Fgf20* are knocked out [Barak et al., 2012]. This is similar during cardiovascular morphogenesis, with partial penetrance when single deletions to *Fgf3* and *Fgf10* occurred together [Urness et al., 2011].

Together, the relatively small number of syndromic craniosynostosis cases associated with mutations in FGF ligands is likely due to ligand redundancies, especially given that the coronal suture expresses 20 of the 22 FGF ligands [Hajihosseini and Heath, 2002]. The spatial-temporal dynamics of FGF signalling, along with the diversity of FGF ligands functioning synergistically, makes biological data difficult to interpret. As biological signals are conveyed through the receptors, targeting FGFRs appear to yield more substantial phenotypes compared to those observed when targeting ligands while allowing direct interpretation to its function.

Other Mouse Models of Human Syndromic Craniosynostosis

Twist1

The *Twist* gene family encodes 2 basic-helix-loop-helix transcription factors: *Twist1* and *Twist2* (also known as *Dermo1*) [Qin et al., 2012]. Originally, *Twist1* was dem-

onstrated to be required for neural tube morphogenesis, while *Twist2* was involved in regulating cytokine gene expression [Chen and Behringer, 1995; Šošić et al., 2003]. *Twist1* plays a variety of roles in mesoderm development focussing mainly in mesenchymal tissue and is expressed in the cranial mesenchyme [Bildsoe et al., 2013]. *Twist1* is expressed prominently in the suture mesenchyme, and its inactivation in mice results in coronal synostosis [Carver et al., 2002; Behr et al., 2011]. This is due to *Twist1* acting as a negative regulator of bone formation where it prevents osteoblast differentiation through *Runx2* inhibition [Bialek et al., 2004]. *Runx2*-deficient mice display delayed osteogenic activity in vivo, but introducing a copy of the *Twist1* null allele into *Runx2*^{+/-} (*Runx2*^{+/-}, *Twist1*^{+/-}) was sufficient to rescue a hypoplastic phenotype [Komori et al., 1997; Bialek et al., 2004]. Conversely, in vitro analysis of *Twist1* knockdown revealed decreased *Runx2* expression with increased apoptosis [Maestro et al., 1999; Yousfi et al., 2001]. Additionally, mutant *Twist1* drives increased expression of *Fgfr2* in vitro and in vivo, perhaps as a compensatory effect, to upregulate the sensitivity of FGF signalling for cellular survival [Connerney et al., 2008; Miraoui et al., 2010]. With regard to disease pathogenesis, autosomal inheritance of LOF mutations in *TWIST1* results in Saethre-Chotzen syndrome [el Ghouzzi et al., 1997; Howard et al., 1997]. Saethre-Chotzen patients display complex suture abolishment most notably coronal, posterior frontal, and lambdoid sutures with digit duplication [el Ghouzzi et al., 1997; Howard et al., 1997]. The first *Twist1* mouse mutant constructed by substituting exon 1 with a *neo*-cassette was described in 1995 in a study of cranial neural tube closure [Chen and Behringer, 1995]. However, these *Twist1* homozygotes were embryonic lethal by E11.5. *Twist1*^{+/-} mice were viable with partial penetrance of limb and craniofacial phenotypes that replicated human disease according to the genetic background of the animals [Bourgeois et al., 1998]. In addition to *Twist1* being a negative regulator for osteogenesis, it also functions to inhibit chondrocyte differentiation. *Twist1*^{+/-} demonstrates enhanced chondrocytic activity in the coronal suture mesenchyme with upregulation of chondrocyte markers such as *Sox9*, *Collagen II*, and *Collagen X*, but its significance is currently elusive [Behr et al., 2011]. Contact inhibition may also play an important role in mediating Saethre-Chotzen syndrome, as both the Notch ligand *Jagged1* (*Jag1*) and the ephrin receptor (*EphA4*) are downstream of *Twist1*. Conditional knockout of either *Jag1* or *EphA4* on a *Twist1*^{+/-} background augments the craniosynostosis phenotype, whilst removal of either *Jag1* or *EphA4* is not sufficient to drive

this pathogenesis [Ting et al., 2009; Yen et al., 2010]. Both of these studies stress the importance of contact inhibition in controlling osteoblast differentiation in the mesenchyme, since conditional removal leads to mis-specification, and loss of positional information in specifying the suture boundary. Additionally, LOF mutations in *JAG1* in humans are associated with Alagille syndrome, linking the pathogenesis of this syndrome to Saethre-Chotzen syndrome [Yen et al., 2010]. bHLH proteins undergo a plethora of roles during development and tend to function as either hetero- or homodimers. bHLH proteins are classified by its tissue distribution, ability to dimerize, and DNA-binding specificities. Class I bHLH proteins are known as E proteins and are abundant in multiple tissue types, whilst Class II, e.g., Twist, have more restricted expression domains. Both Class I and Class II HLH proteins contain the basic domain and are DNA binding. Conversely, Class III proteins, which include Id, facilitate dimerization with E proteins and perturb formation of heterodimers between Class I/II proteins [Massari and Murre, 2000]. The degree of *Twist1* syndromic craniosynostosis is related to their binding partners and the dimers they form. For example, a severe craniosynostosis phenotype is caused by a frameshift in *Tcf12* in a *Twist1* background (*EIIa^{CRE/+}, Tcf12^{flox/-}, Twist1^{+/+}*) [Sharma et al., 2013]. *Tcf12* is an E protein, and the inability to form the Twist1-Tcf12 heterodimer results in a severe phenotype. The same scenario occurs to LOF of bHLH inhibitors *Id1* and *Id3* under a *Twist1* heterozygous background, with the former showing greater penetrance (*Id1^{+/-}, Twist1^{+/-}*) [Connerney et al., 2008].

Msx2

Mutations in *MSX2* are associated with Boston type craniosynostosis [Jabs et al., 1993]. Substitution of a histidine 148 to a proline (p.His148Pro) increases the binding affinity of *MSX2* to its target DNA sequence [Ma et al., 1996]. *Msx2* is expressed in the sagittal and lambdoid sutures of the mouse, and its overexpression, which can be either of a wild-type allele or through a GOF mutation (*Msx2^{P7H/+}*), leads to narrowing of the sagittal suture and abnormal bone overgrowth, particularly to the parietal bone [Liu et al., 1995]. In contrast, *MSX2* haploinsufficiency in humans leads to an ectopic calvarial foramen and delayed suture closure, due to the loss of binding affinity to target DNA [Wilkie et al., 2000]. A similar observation is reported upon knockout of *Msx1* and *Msx2* in vivo [Roybal et al., 2010]. The ectopic foramen was not a consequence of an embryonic patterning defect, but rather a mitotic decrease in the bone, likely from the ossifica-

tion centre [Ishii et al., 2003; Roybal et al., 2010]. *Msx2* and *Twist1* interact to coordinate cellular proliferation and differentiation: firstly, haploinsufficiency of both genes leads to ectopic frontal foramen formation and secondly, knockout of both alleles results in increased phenotypic severity [Ishii et al., 2003]. Analysis of embryos between E12.5 and E14.5 revealed that the pathogenesis is mainly a reduction of osteoblast differentiation at E12.5. It is interesting to note that the transcripts of these genes do not display the same expression pattern embryonically, but do lead to the same phenotypic outcome. Therefore, this suggests these transcription factors may work synergistically as a co-factor to derive the same phenotype at the protein level [Ishii et al., 2003].

Hedgehog-Related Genes

Gli3 LOF is associated with Greig cephalopolysyndactyly (GCP). GCP is an autosomal dominant disorder affecting both limb and craniofacial development [Hui and Joyner, 1993]. The most notable characteristic includes supernumeric fingers (polydactyly), macrocephaly, and a broad forehead with an additional phenotype being lambdoid synostosis [Rice et al., 2010]. *Gli3* is primarily a repressor of Hedgehog signalling, which its LOF exacerbates, resulting in GCP. Specifically, GCP is caused by deletions to 7p13 in the human chromosome and is also mapped to the same region in the mouse genome [Hui and Joyner, 1993]. Johnson [1967] developed the first mouse model “Xtra Toes”, *Gli3^{Xt-/Xt-}* (Xt-J), carrying an intragenic deletion of *Gli3* [Johnson, 1967; Hui and Joyner, 1993]. Augmented Hedgehog signalling is related to Carpenter syndrome, through LOF to *RAB23* (Ras-related protein Rab23) – a separate negative regulator of Hedgehog signalling preventing signalling transduction through *Gli2* repression [Eggenchwiler et al., 2006; Jenkins et al., 2007]. Carpenter syndrome patients display pan synostosis, but *Rab23^{-/-}* mice do not recapitulate this phenotype and are embryonically lethal [Eggenchwiler et al., 2001]. Thus, the *Gli3^{Xt-/Xt-}* was used to study Hedgehog misregulation in craniosynostosis instead [Rice et al., 2010]. Further analysis of *Gli3^{Xt-/Xt-}* reveals ectopic osteoblast differentiation in the lambdoid sutures, which leads to early suture abolishment. Lambdoid synostosis can be rescued through augmentation of FGF signalling, which upregulates expression of *Twist1* [Rice et al., 2000; 2010]. Interestingly, missense mutations in human *MEGF8* (multiple EGF like domain 8) phenocopies features observed in Carpenter Syndrome [Twiggy et al., 2012]. Additionally left-right asymmetry and cardiac defects were also reported in a mouse mutant (*Megf-*

$8^{C193R/+}$) generated as a result of a large-scale mutagenesis screen [Aune et al., 2008; Zhang et al., 2009]. However, craniofacial or skeletal defects were not analysed in this study. It is unclear as to the role of *Megf8* during development, but the close resemblance between *MEGF8* and Carpenter syndrome suggests the mechanism responsible is highly similar. One might speculate effects on early development, and given by the abnormalities in left-right asymmetry, it is likely to affect both Nodal and Hedgehog signalling. This is supported by the recent demonstration that *Megf8* dampens Hedgehog signalling in the primary cilia and that could explain the phenotypic similarities to Carpenter syndrome caused by *RAB23* mutation [Pusapati et al., 2018].

Masp1 and Colec11

Masp1 (mannose-associated serine protease 1), *Colec10*, and *Colec11* (Collectin subfamily 10 and 11) are components of the lectin pathway that is associated with inflammation. Mutations in these genes contribute to the pathogenesis of 3MC syndrome [Rooryck et al., 2011; Urquhart et al., 2016; Munye et al., 2017] which is the collective term for multiple related syndromes (Carnevole, Mingarelli, Malpuech, and Michels syndromes) [Titomanlio et al., 2005]. Common clinical features include craniosynostosis, cleft palate, hypertelorism, hearing deficits, growth deficiencies, and heart defects [Titomanlio et al., 2005], which are consequently suggested to be affected during development by abrogation to cytokine signalling [Newton and Dixit, 2012]. Multiple amino acid changes in *MASP1* and *COLEC11* have been identified in human patients, predominantly resulting in a frameshift and LOF of the mature protein [Rooryck et al., 2011]. There is no mouse model that describes 3MC at present. However, a double knockout of *Masp1* and *Masp3* (*Masp1/3^{+/-}*) is reported in the literature without describing any obvious role in craniofacial development [Takahashi et al., 2008].

Hdac4

Histone deacetylases (HDAC) modulate gene expression by altering chromatin structure and repressing transcription factors. Brachydactyly mental retardation syndrome occurs as a consequence of LOF of *HDAC4* [Williams et al., 2010], commonly due to deletion of the Chr2q37 region that includes the *HDAC4* gene. Clinical presentation of this syndrome includes craniofacial dysmorphology with craniosynostosis, developmental delay, obesity, and mental deficit on the autistic spectrum [Williams et al., 2010]. HDAC4 can bind to the *Runx2* pro-

motor and as such is a regulator of the rate of ossification [Vega et al., 2004]. *Hdac4^{-/-}* mice show premature ossification of endochondral structures, whilst overexpression of *Hdac4* in the chondrocytic lineage (*Col2a1-Hdac4*) results in cartilage dysplasia [Vega et al., 2004]. However, the authors did not report any craniofacial abnormalities in the *Hdac4* knockouts. The contribution of the role of (endochondral) cartilage in the process of suture abolishment remains elusive, despite a recent study showing that ectopic chondrocytes invading the suture mesenchyme lead to endochondral ossification in a PDGFRa mutant [He and Soriano, 2017].

TGF Signalling Misregulation

TGF β signalling misregulation is associated with Marfan syndrome, a rare disorder occurring in approximately 1:5,000 individuals [Judge and Dietz, 2005]. Marfan syndrome is a complex disease affecting multiple systems, including craniofacial and skeletal dysmorphology, cardiovascular abnormalities, tissue fibrosis, ocular, and mental deficits [Judge and Dietz, 2005]. Loeys-Dietz disease and Shprintzen-Goldberg syndrome have a varying phenotypic spectrum of the described marfanoid phenotype [Judge and Dietz, 2005; Loeys et al., 2005; Carmignac et al., 2012; MacCarrick et al., 2014]. In particular, patients with marfanoid phenotype and craniosynostosis are commonly referred to as Shprintzen-Goldberg syndrome. Missense mutations in the extracellular matrix protein Fibrillin 1 (*FBN1*) was first identified to be associated with Marfan syndrome and has been implicated in craniosynostosis [Dietz et al., 1991; Sood et al., 1996]. However, multiple knockin models have been described in the mouse without recapitulating craniosynostosis [Pereira et al., 1999; Judge et al., 2004; Ng et al., 2004; Carta et al., 2006]. Mutations causing LOF of the TGF signalling repressor, *SKI*, are associated with Shprintzen-Goldberg syndrome, indicating a potential role for this signalling pathway in craniosynostosis [Carmignac et al., 2012; Doyle et al., 2012]. Mutations in *TGFBR1* and *TGFBR2* were identified as the cause of Loeys-Dietz disease [Loeys et al., 2005], a condition that typically presents with cardio-ventricular and outflow tract abnormalities, cleft palate, hypertelorism, and occasionally craniosynostosis [Loeys et al., 2005]. Substitution mutations in *TGFBR1* and *TGFBR2* augment TGF signalling activity, as shown by an increase of the pSMAD readout, and are therefore considered as GOF mutations [Loeys et al., 2005]. Craniosynostosis of varying severity has been reported in mice with mutations in both of these receptors (*Tgfbr1^{M318R/+}* and *Tgfbr2^{G357W/+}*) [Gallo et al., 2014]. In

particular, *Tgfb1*^{M318R/+} has partial coronal synostosis with additional kyphosis in the thoracic region [Gallo et al., 2014].

Mouse Models Indirectly Associated with Human Syndromic Craniosynostosis

The previous sections described mouse mutants that model human mutations causing syndromic craniosynostosis. In addition, there are numerous mouse mutants that are not based on human genetic mutations (i.e., knockin mutants) that also exhibit craniosynostosis. A substantial number of these mutants are related to growth factor signalling misregulation. Further to *Fgfr2*^{C342Y/+}, isoform-specific knockouts such as *Fgfr2b*^{-/-} and *Fgfr2c*^{-/-} also display a craniosynostosis phenotype [De Moerlooze et al., 2000; Eswarakumar et al., 2002]. In particular, *Fgfr2c*^{-/-} mice show coronal synostosis that phenocopies the *Fgfr2c*^{C342Y/+} mutant [Eswarakumar et al., 2002]. The main difference between both models lies within the disease progression, where the latter shows an accelerated phenotype during early embryogenesis [Eswarakumar et al., 2002, 2004]. *Fgfr2b*^{-/-} displays a subtle form of craniosynostosis, with fusion of the parietal and squamous temporal bones [De Moerlooze et al., 2000]. It is well established that a hallmark of craniosynostosis is the upregulation of the MAPK/ERK pathway. Indeed, knockout of (*Dusp6*^{-/-}) a negative regulator of ERK results in coronal synostosis [Li et al., 2007]. Similarly, LOF mutations of the Ets2 repressor factor (*ERF*) are also implicated in compound craniosynostosis to the coronal and sagittal sutures [Twigg et al., 2013]. ERF is responsible for the export of active ERK from the nucleus in order to attenuate its transcriptional activation activities, and conditional knockout of ERF (*Erf*^{fllox/-}) recapitulates the phenotype observed in patients with LOF mutations [Twigg et al., 2013].

Although not commonly associated with human craniosynostosis, platelet-derived growth factor (PDGF) signalling has also been related to craniofacial malformations and coronal synostosis [Soriano, 1997; Moenning et al., 2009; He and Soriano, 2017]. This is most likely due to the conserved nature of growth factor signalling downstream of the receptor. Signalling misregulation in an isoform of the platelet-derived growth factor receptor PDGFR α , is implicated in midline defects and a split face (*Pdgfra*^{-/-}) [Soriano, 1997]. Moreover, over-activation of PDGFR α (*Pdgfra*^{D842V/+}) drives ectopic chondrogenesis eliciting coronal and lambdoid synostosis through the

P13K-AKT cascade [He and Soriano, 2017]. A similar phenotype is replicated in a transgenic overexpression model located at the *Rosa26* locus (*R26R*^{Pdgfra-D842V/+}) [Moenning et al., 2009].

In addition to the already mentioned growth factors, Wnt/ β -catenin signalling is also a key player in regulating osteoblast proliferation and differentiation [Yu et al., 2005]. In the absence of signalling activation, β -catenin is prevented from being translocated to the nucleus through degradation. Therefore, Wnt signalling modulators are critical to modulate signalling sensitivity. Axin serves as a scaffold for formation of a β -catenin degradation complex, and its degradation is therefore Axin dependent [Logan and Nusse, 2004]. Augmentation of Wnt signalling by *Axin2*^{-/-} results in coronal and interfrontal synostosis [Yu et al., 2005]. Similarly, overexpression of the Nel-like type 1 molecule (*NELL1*) elicits posterior frontal suture craniosynostosis, along with the partial closure of sagittal and coronal sutures [Zhang et al., 2002]. *NELL1* was originally isolated from samples obtained from unilateral (non-syndromic) coronal synostosis patients and is expressed in the mesenchyme and osteogenic fronts [Ting et al., 1999]. *NELL1* expression is upregulated in sutures undergoing premature fusion, and is believed to augment Wnt/ β -catenin signalling, through interactions with β -integrins in osteoblasts [Ting et al., 1999; James et al., 2015].

There are a number of other craniosynostosis mutants reported in the literature. Growth differentiation factor 6 (*Gdf6*) is a secreted morphogen associated with the BMP signalling pathway [Ducy and Karsenty, 2000]. Mutants lacking both alleles of *Gdf6* (*Gdf6*^{-/-}) display coronal synostosis and appendicular skeleton abnormalities, with fusion of the tarsals and carpals [Settle et al., 2003]. *Runx2* is indispensable for osteoblast differentiation, and overexpression of *Runx2* in the mesenchyme, driven under the endogenous promoter *Prx1* (*Prx1-Runx2*), elicits multiple synostosis inclusive of multiple joint fusions in the appendicular skeleton [Maeno et al., 2011]. Metopic suture synostosis is caused by LOF mutations in Frs1 related extracellular related gene 1 (*FREM1*) and is a cause of trigonocephaly in humans [Vissers et al., 2011]. *Frem1* encodes a protein secreted by mesenchymal cells that aids extracellular matrix remodelling [Smyth et al., 2004]. In the mouse, *Frem1* is expressed along the periphery of the frontal bone, immediately adjacent to the interfrontal suture (metopic equivalent) [Vissers et al., 2011]. The original mouse model ENU by mutagenesis *Frem1*^{Bat/+} is a hypomorph caused by exon skipping [Smyth et al., 2004], and an exon 2 knockout mouse is also

available, *Frem1^{qbrick/+}* [Kiyozumi et al., 2006; Vissers et al., 2011]. Both models harbour interfrontal synostosis, with the latter mutant possessing a stronger phenotype [Vissers et al., 2011].

Conclusion and Future Directions

Mouse models have been critical to the study of human disease. Together with lineage tracing reporters, the phenotypes caused by knockin mutations have been critical to understand the pathways required for craniofacial development. Furthermore, mouse models provide a platform to test novel therapeutic strategies and management techniques [Perlyn et al., 2006; Wang et al., 2015; Maruyama et al., 2016; Rachwalski et al., this issue]. However, it is well understood in the murine research community that mouse models of human disease sometimes exhibit differences in phenotypic end points, which might simply be due to species differences. These can be the result of differing genetic redundancies and sensitivities. An example of this can be seen for a *RAB23* mutation responsible for human Carpenter syndrome [Eggenchwiler et al., 2001; Jenkins et al., 2007]. LOF of the mammalian homologue of *RAB23* in the mouse results in exencephaly and early embryonic lethality implicating dosage dependency of the phenotype [Eggenchwiler et al., 2001]. Other examples include the Ets domain-containing transcription factor (*ERF*), where craniosynostosis is only observed in a mouse model harbouring a conditional allele (*Erf^{fl/-}*) reducing the expression level to about 30% in contrast to that of a heterozygote null allele (*Erf^{dl1/-}*), where the reduction would be 50% [Papadaki et al., 2007; Twigg et al., 2013]. Similar can be said of those mouse models related to Marfan syndrome that do not recapitulate a craniofacial phenotype [Judge et al., 2004; Ng et al., 2004; Pereira et al., 1999; Gallo et al., 2014].

The ability to generate gene knockout models has been pivotal in our understanding of gene function, and this in turn is dependent upon successful and accurate targeting of the specific allele of interest. Therefore, it makes sense that the overall design of a targeting vector is vital to reproduce a consistent phenotype. However, there are instances in the literature where a wide phenotypic spectrum can be produced. Examples of this can be seen in the *Fgfr2* knockouts as the receptor protein has multiple functionalities [Yu et al., 2003; Molotkov et al., 2017]. A common strategy to generate an *Fgfr2* knockout is through the removal of the ligand-binding domain (exons 8–9, IgI loop3). However, this mutant does not result in the com-

plete removal of the FGFR2, but instead yields a truncated, albeit non-functional, receptor. On the other hand, removal of exon 5, common to both *Fgfr2b* and *Fgfr2c* isoforms, did not lead to the expression of a truncated receptor [Yu et al., 2003; Molotkov et al., 2017]. In fact, there are slight phenotypic differences too between these knockouts, with the latter *Fgfr2c* knockout appearing less severe [Yu et al., 2003; Molotkov et al., 2017]. Targeting constructs recombined between intragenic regions also have an effect on gene expression. Here, removal of exon 9 encoding *Fgfr2c* is able to cause a splice switch that results in ectopic *Fgfr2b* expression [Hajihosseini et al., 2001]. LoxP sites were inserted into intergenic regions of *Fgfr2* exons 8–10, and conditional removal through recombination seems to have increased susceptibility to alternative splicing alterations [Hajihosseini et al., 2001]. The upregulation of *Fgfr2b* subsequently shifted the phenotype from a Crouzon spectrum to that of Apert [Hajihosseini et al., 2001]. Nonetheless, the successful targeting of specific genes has been vital to determine gene function contributing towards human disease.

The advancement of CRISPR-CAS9 will increase efficiency of generating novel mouse models for human disease [Singh et al., 2015]. Conventional techniques generating mouse models with recombination technology has been slow and expensive, and the use of genome editing technologies could overcome these issues. This could be particularly useful in systematic phenotypic screens for mouse embryos [Adams et al., 2013]. There is an international effort to delineate the phenotypes of knockout mice generated from the International Knockout Mouse Consortium (IKMC). The International Mouse Phenotyping Consortium (IMPC) (<http://www.mousephenotype.org/>), as it became known, aims to phenotypically screen 20,000 knockouts in 10 years [Adams et al., 2013]. The importance of screening phenotypes allows the corroboration between genotype to phenotype and especially in the case of embryonic lethal models that helps to pinpoint critical pathways for development. There are several methods for analysis, with emphasis on 3D imaging such as μ CT, optical projection tomography, and high-resolution episcopic microscopy. The ultimate aim is to utilise these tools to generate data widely available to researchers. A similar platform is also available specifically aimed for craniofacial development called “FaceBase” (<http://www.facebase.org/>), which has a wide range of curated datasets available online, both phenotypic and omics, for craniofacial research across multiple organisms. Several groups have contributed to this consortium by generating transcriptomic atlases of calvarial sutures acquired using

laser capture microdissection on several mouse models of craniosynostosis including Apert and Saethre-Choetzen syndromes.

Despite the plethora of mouse models generated for craniofacial syndromes, few studies have characterised the downstream signalling misregulation that must contribute to the phenotype. Further disruption of downstream effectors will undoubtedly help to delineate the complex relationship between signal transduction and gene expression. This could be achieved by generating mouse models specifically targeting those signalling intermediates. A comprehensive review of these mouse models has been listed in a recent paper by Dinsmore and Soriano [2018]. As growth factor signalling, such as FGF, is critical for craniofacial development, it would also be ideal to adopt mouse models that are designed to study cancer progression into birth defects research. This is because mouse models such as *Braf*^{V600E/+} or *Kras*^{G12D/+} have mutations that specifically disrupt multiple levels of a signalling cascade (i.e., MAPK/ERK) [Tuveson et al., 2004; Mercer et al., 2005]. Future studies will need to address the impact of the mutation on cascade activation at the level of the receptor in vivo. For example, it has been demonstrated by Miraoui et al. [2009] that the Apert mutation (FGFR2-p.S252W) preferentially activates the PLC-PKC cascade for osteogenesis in vitro [Miraoui et al., 2009]. There have been attempts in the past to elucidate this by mutating binding domains on the catalytic domains of PDGFRs in the mouse [Klinghoffer et al., 2001, 2002; Fantauzzo and Soriano, 2016]. As generating

a mouse mutant for individual binding domain is time consuming, technologies such as CRISPR-CAS9 will no doubt assist with this endeavour.

In conclusion, mouse models offer a robust platform to study craniofacial birth defects. This is in particular to clinical syndromes, where a majority of knockin mice carrying a human mutation recapitulates the human disease phenotype. Together with conditional mouse models, significant progress has been made to dissect the molecular basis for delineating craniofacial birth defects. With the dawn of genome-editing technologies, there are exciting opportunities over the horizon, and it is doubtless that mouse models will continue to play a central part in biomedical science.

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